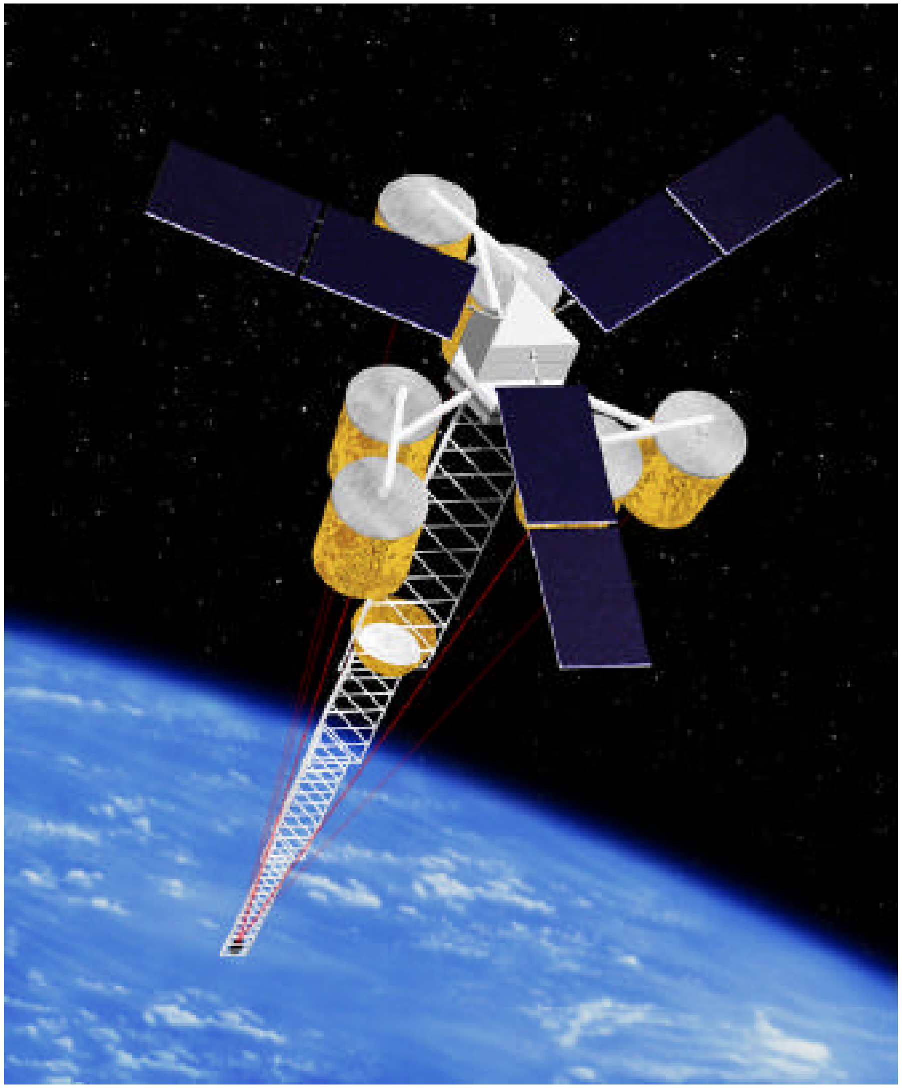
Optical Controls Design and Validation for a Space Based Sparse Aperture Telescope



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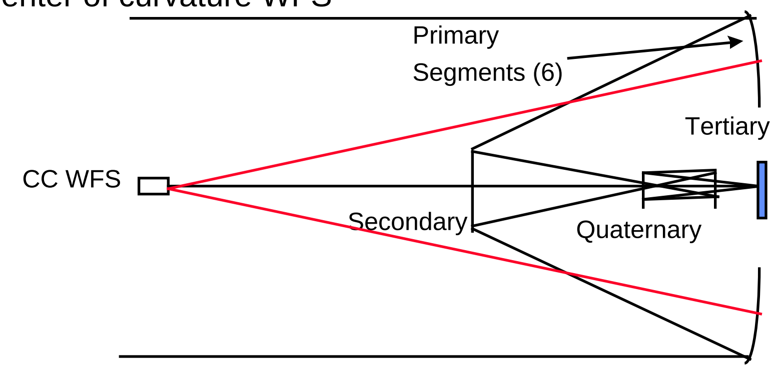
Low Cost Space Imager

Lab Experiment Validates Space Controls Concept

Space Telescope - Golay 6 Primary Arrangement

- Spherical primaries
- 4 element design
- Center of curvature WFS



Space telescope tolerances set for 0.2 deg TFOV

Key Tolerances

Primaries

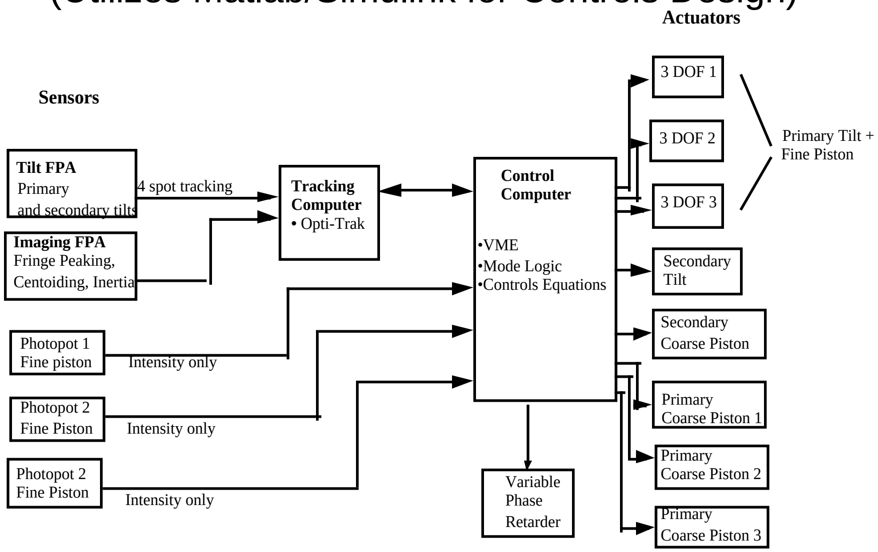
Piston Error 38 nm
Tilt Error - 17 nrad
Translation & Rotation - Not Applicable!

Secondary

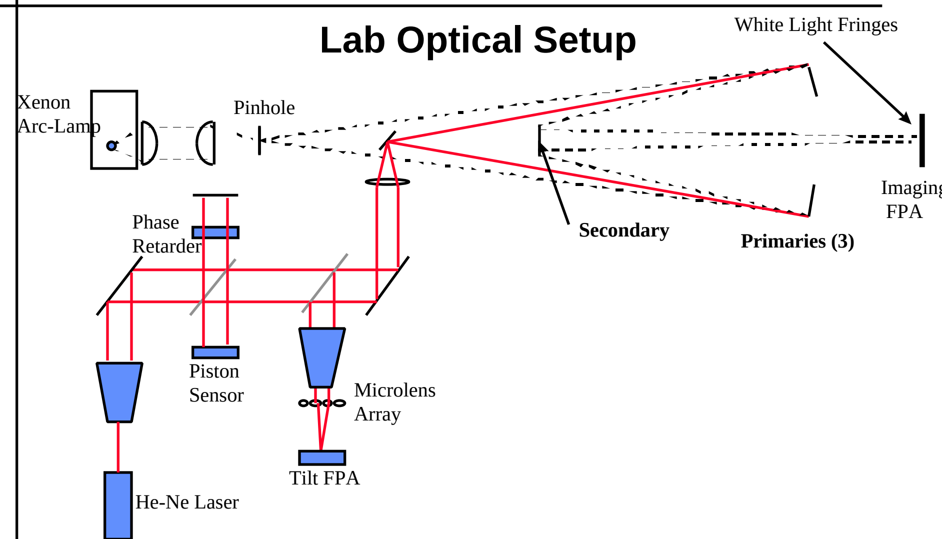
Tilt Error - 850 nrad

Lab Controls Computer

(Utilizes Matlab/Simulink for Controls Design)



Lab Optical Setup



Validates

- Center of Curvature WFS Concept
- Automatic Phasing Control System

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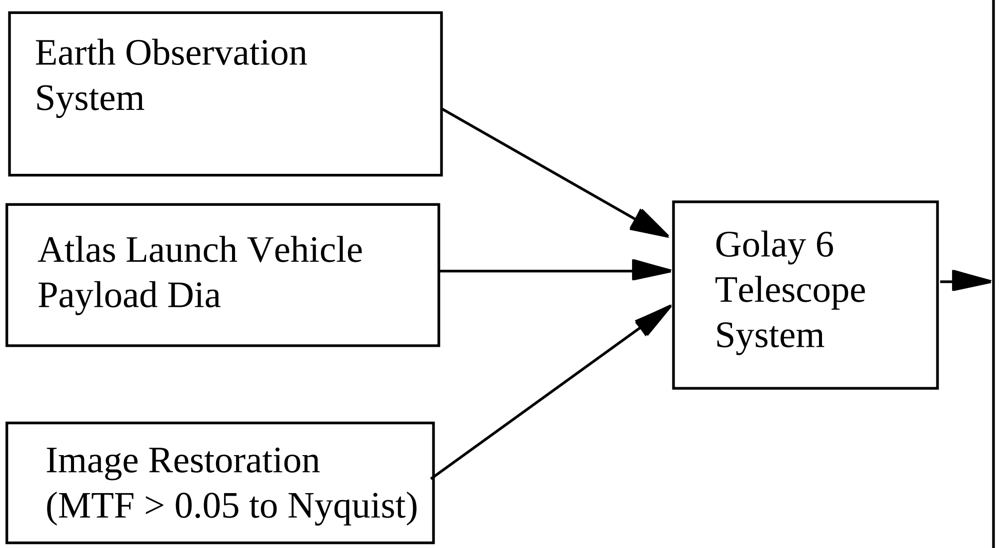
Requirements Analysis Summary



Requirements

Parameter	**Value**
Altitude	6.1 Mm
System Diameter	11.4 m
Segment Diameter	2.2 m
Effective Optical Dia.	8.0 m
Primary F/#	F/1.5
System Focal length	90 m
Spectral Band	0.5 to 0.9 um
Total FOV	0.19 deg.
IFOV	81 nrad
Pixel size	7.3 um
Image size	0.292 m
Image quality	MTF > 0.05 at Nyquist (68.5 cy/mm)

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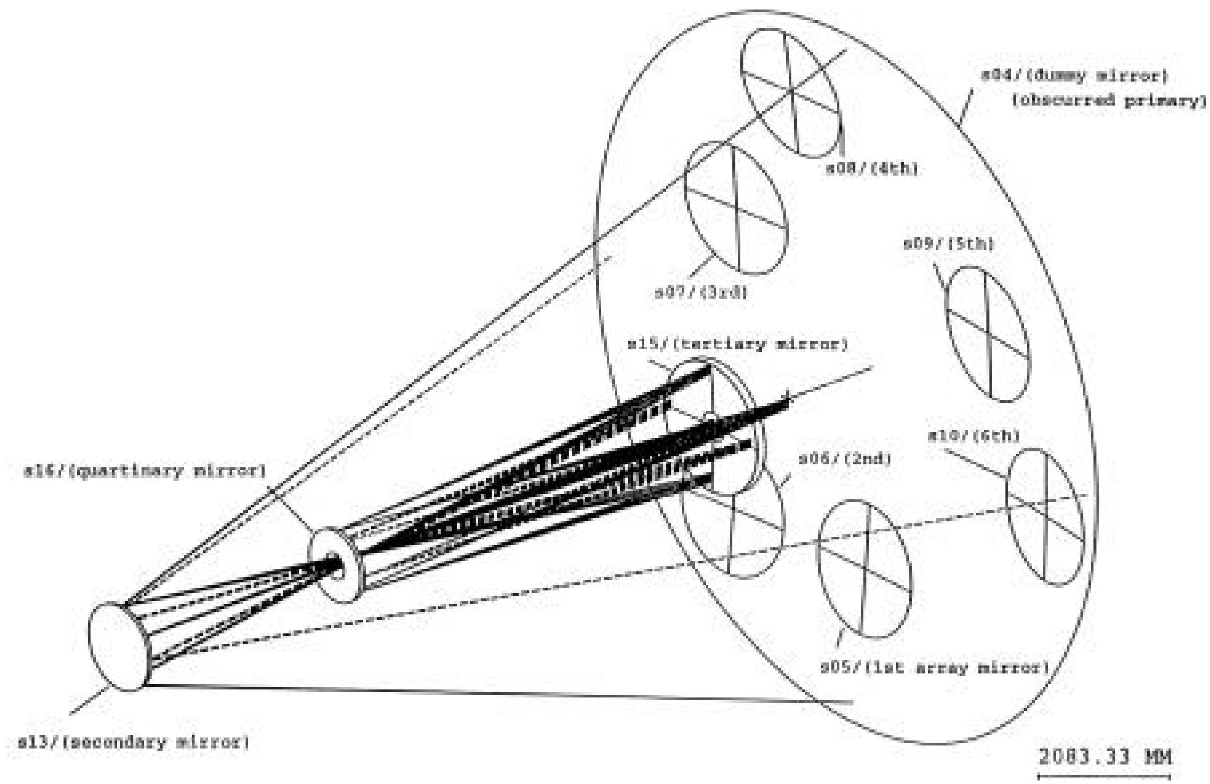
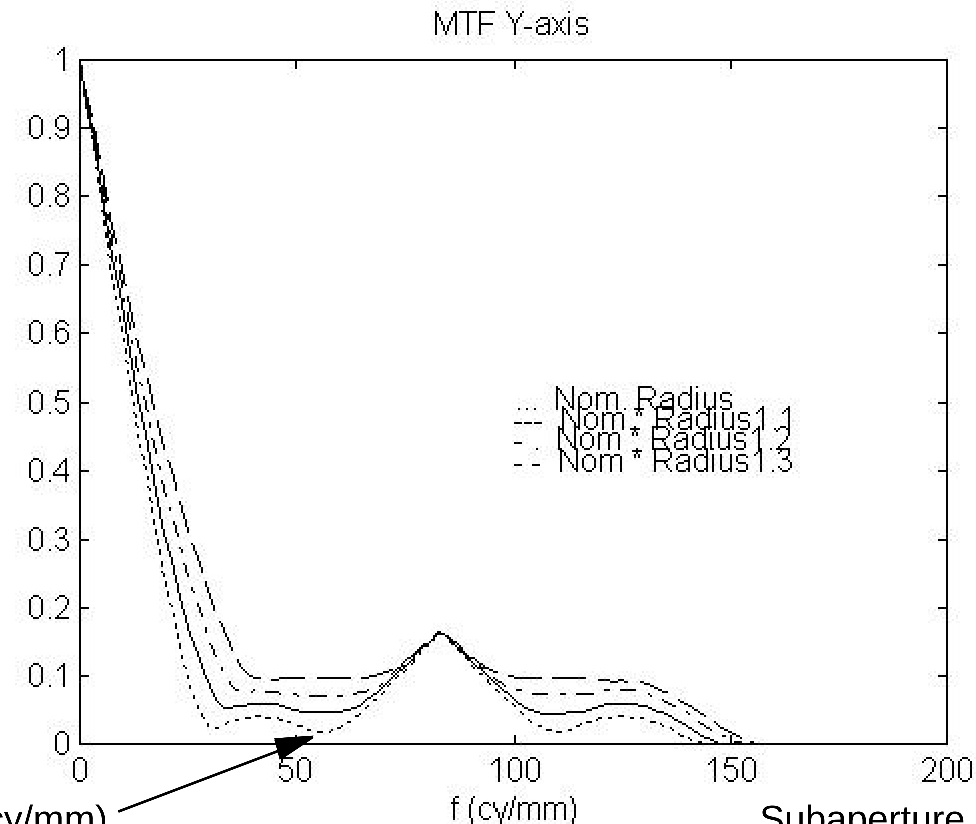
Golay 6 Telescope Design



Design basis:	Sasian, J., “Flat-field, anastigmatic, four-mirror optical system for large telescopes” Opt. Eng., Dec 87, Vol 26 No 12.
Performance:	Diffraction limited polychromatic TFOV 0.2 deg, 0.5 to 0.9 micron, Dia 11.4 m (circumscribed), F/7.8
Elements:	Spherical Primary segments, all other are aspheric, 4rt has 0.5 mm departure from best sphere
Other:	PAMELA used similar design, Reimaged pupil at tertiary makes excellent location for deformable mirrors
Designer:	Don Koch, ORA, Pasadena, CA

MTF Analysis

(Nominal Golay 6 Configuration produces Zeros in MTF)



- Near Zero Value (60cy/mm)
- As Radius of Subaperture Increases, MTF is raised
- Image Restoration Filter

$$Gain(f) \quad \frac{MTF_{monolith}(f)}{MTF_{Golay}(f)}$$

- Keep MTF large to avoid high gain in filter (noise)

Subaperture Diameter

- Nominal 1.8 m
- Increased to 2.2 m

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Optical Phasing Error Budget

Nominal MTF (60 cy/mm @ 0.1 deg)	**0.056**
Degraded MTF (60 cy/mm @ 0.1 deg)	**0.032**

MTF Degradation
0.024

Primary Mirrors — 0.013

Tilt X	17 nr	0.005
Tilt X	17 nr	0.005
Piston	38 nm	0.007
Figure (Sag + Cylinder)		0.003

Secondary — 0.007

Tilt X	0.85 ur	0.004
Tilt Y	0.85 ur	0.002
Axial Disp	61 um	0.001
Translation X	0.2 mm	0.001
Translation Y	0.2 mm	0.002
Figure (Sag + Cylinder)		0.002

Tertiary — 0.009

Tilt X	19 ur	0.003
Tilt Y	100 ur	0.002
Axial Disp	78 um	0.003
Translation X	3 um	0.002
Translation Y	3 um	0.004
Figure (Sag + Cylinder)		0.002

Quartenary — 0.007

Tilt X	50 ur	0.001
Tilt Y	50 ur	0.000
Axial Disp	0.17 mm	0.004
Translation X	0.2 mm	0.002
Translation Y	0.2 mm	0.002
Figure (Sag + Cylinder)		0.002

Physical values shown correspond to mirror motion

Optical Elements and the Controls Required

Element	DOF	Control Type
Primaries	Rotation	None
	Translation	None
	Tilt	Maintenance
	Piston	Maintenance
Secondary	Translation	Maintenance
	Tilt	Maintenance
	Piston	Maintenance
Tertiary	Translation	Calibration
	Tilt	Calibration
	Piston	Calibration
Quaternary	Translation	None
	Tilt	None
	Piston	None

Control Types

- **None -** Initial Deployment accy. or Vib/Thermal induced errors are small compared to tolerance
- **Calibration -** Element tolerance warrants one time on orbit adjustment, but not continuos control
- **Maintenance -** Element tolerance exceeds capability of thermal/vibration control, constant control is required

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Alignment System Requirements Vary with Imaging Operations Timeline

Spacecraft Pointing	Slew Accel.	Constant Slew During Imaging	Slew Accel.	Constant Slew During Imaging	Slew Accel
	← CMG Unbalance →				
Disturbances	Slew Torque Disturb.	Actuator Cross Coupling	Slew Torque Disturb.	Actuator Cross Coupling	Slew Torque Disturb.
Alignment System Function	Maintain Loop Closure	Achieve Imaging Disturbance Residuals	Maintain Loop Closure	Achieve Imaging Disturbance Residuals	Maintain Loop Closure

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OPTICAL CONTROLS
TOP LEVEL REQUIREMENTS

- PRECISELY CONTROL THE OPTICAL LINE OF SIGHT AND OPTICAL PATH DIFFERENCES OF A SEGMENTED PRIMARY MIRROR OPTICAL SYSTEM, WITH SUFFICIENT PRECISION TO PRODUCE A NEAR DIFFRACTION IMAGE. INCLUDES:
  - DEPLOYMENT OF PRIMARY SEGMENT BOOMS
  - POINTING AT A SPECIFIC TARGET
  - TILT AND PISTON ACQUISITION
  - TILT AND PISTON CONTROL DURING IMAGING

- STRUCTURAL REQUIREMENTS
  - PROVIDE SUPPORT FOR THE OPTICAL COMPONENTS ON BOOMS
  - BOOMS MUST HAVE FIRST SIGNIFICANT MODES ABOVE THE OPTICAL CONTROL BANDWIDTHS
  - USE ISOLATION AND DAMPING TO REDUCE STRUCTURAL MOTION SUCH THAT OPTICAL CONTROL IS NOT REQUIRED FOR VIBRATION FROM CMG AND ACCELERATION TORQUES
  - STRUCTURAL RESPONSE TO THERMAL EFFECTS MUST BE SMOOTH - NO “CLICKS” LIKE SPACE TELESCOPE

- SENSOR REQUIREMENTS ARE NOT STRESSED BY SNR - BRIGHT SOURCES USED FOR ACQUISITION AND CLOSED LOOP CONTROL

- OPTICAL CONTROL REQUIREMENTS
  - DURING SLEW ACCELERATION - MAINTAIN CLOSED LOOP (DON’T BREAK LOCK)
  - DURING CONSTANT SLEW IMAGING - REJECT EFFECT OF THERMAL DEFORMATION AND MEET PHASING BUDGET

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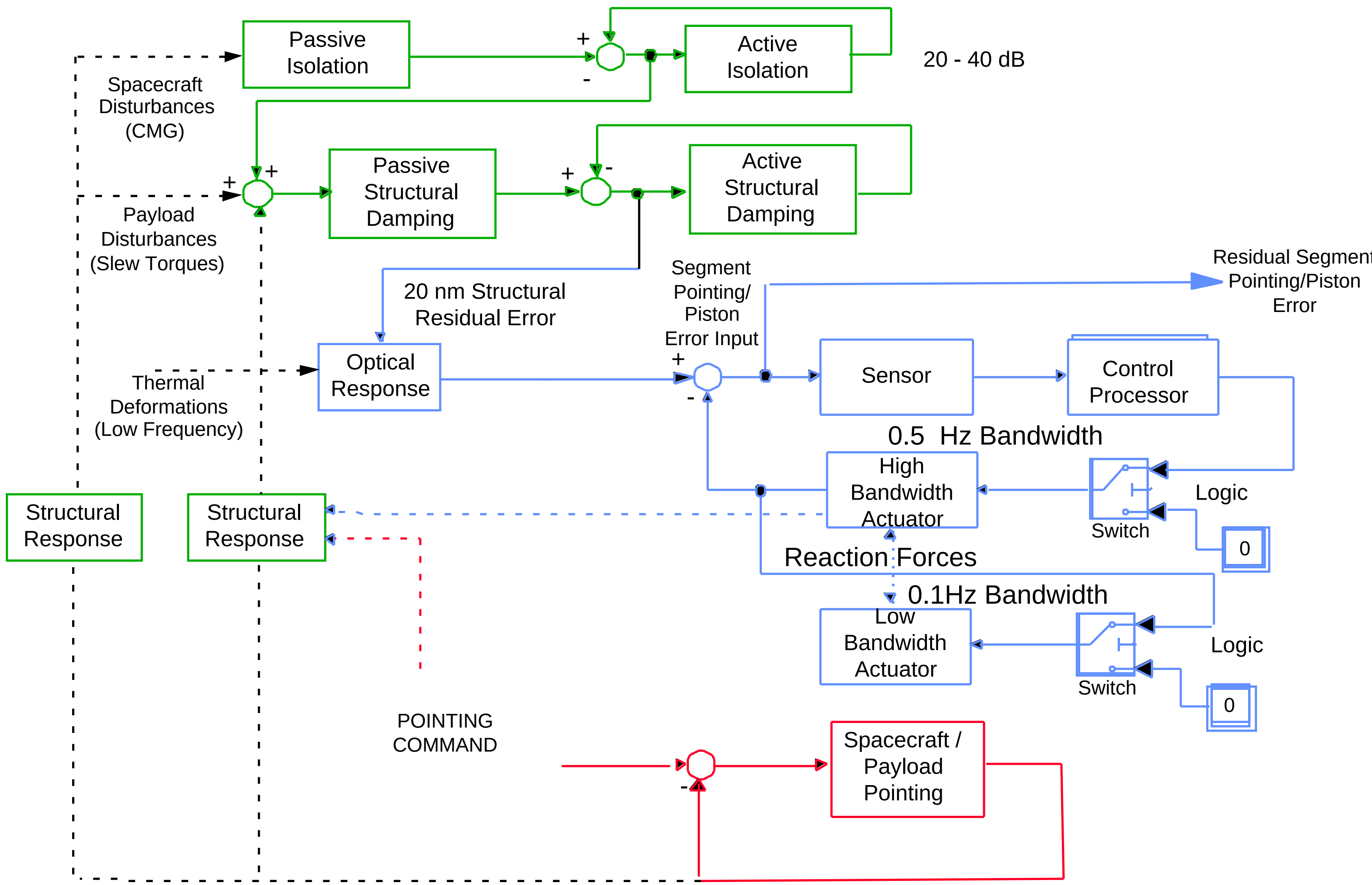
CONTROL FUNCTION ALLOCATION

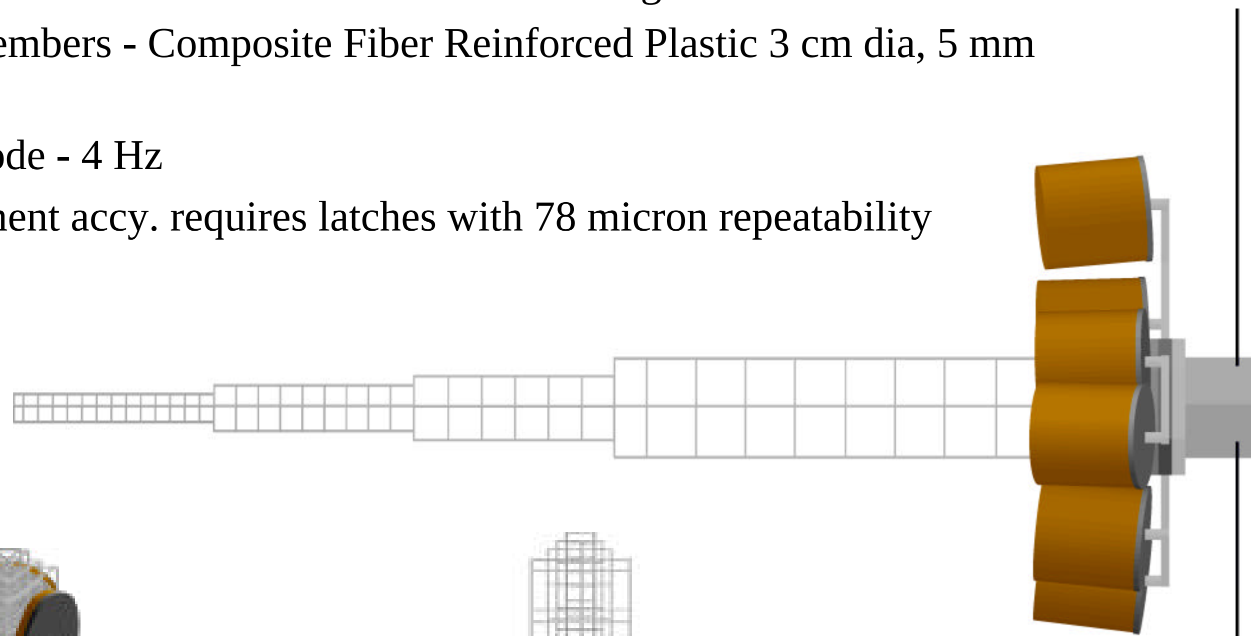
FUNCTION	CONTROL ELEMENT	SENSOR
PAYLOAD ISOLATION	HONEY WELL HEXAPOD	POSITION SENSORS BETWEEN SPACECRAFT AND PAYLOAD
PAYLOAD STRUCTURAL DAMPING	PASSIVE DAMPING TREATMENT	NONE
BOOM STRUCTURAL CONTROL	REACTION MASS ACTUATORS	DISTRIBUTED ACCELS
SUBAPERTURE TILT	PRIMARY SEGMENT TILT	METROLOGY SENSORS
SUBAPERTURE PISTON	PRIMARY SEGMENT PISTON	METROLOGY SENSORS
OTHER MTF	SECONDARY 5 DOF	FPWFS AND METROLOGY SENSORS
OTHER MTF	5 DOF TERTIARY	FPWFS
PRIMARY SEGMENT TILT /PISTON OFFLOAD	SEGMENT SUPPORT STRUCTURE	SEGMENT POSITION SENSOR

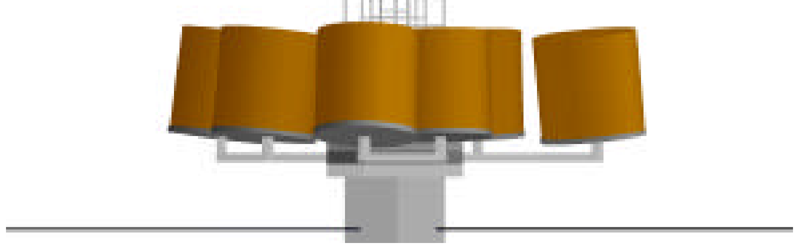
HIERARCHICAL CONTROL AND NESTED LOOPS PROVIDE MULTIPLE LAYERS OF DISTURBANCE REJECTION



Secondary Boom Is Packageable in ATLAS 2AS

- Package volume fits within Atlas 2 AS launch fairing
- Boom truss members - Composite Fiber Reinforced Plastic 3 cm dia, 5 mm thick
- 1st flexible mode - 4 Hz
- 3 mm deployment accy. requires latches with 78 micron repeatability





LCSI Experiment is Traceable and Scaleable to System Concept

- Traceable- experiment configuration "looks like" system concept
  - Full fidelity control architecture
    - Correct loop interactions, actuators, and control bandwidths
  - Same mode control sequencing and functionality
    - Acquisition, coarse and fine tilt, etc.
  - Same sensing schemes for optical errors
  - Optical and mechanical disturbance spectra consistent with analysis
- Scaleable - experimental performance goals are consistent with (scaled) system requirements
  - Tilt requirements scale with lambda/D
  - Piston does not scale

Parameter	Space System	Lab Demo	Units
Subaperture Diameter	2.2	0.05	m
Secondary Diameter	1.4	0.1	m
Primary Tilt Tolerance	17.0E-9	750.0E-9	rad
Primary Piston Tolerance	38.0E-9	38.0E-9	m
Secondary Tilt Tolerance	850.0E-9	11.9E-6	rad
Secondary Piston Tolerance	61.0E-6	61.0E-6	m

White Light Fringe Visibility Budget

Defines Lab Experiment Phasing Requirements

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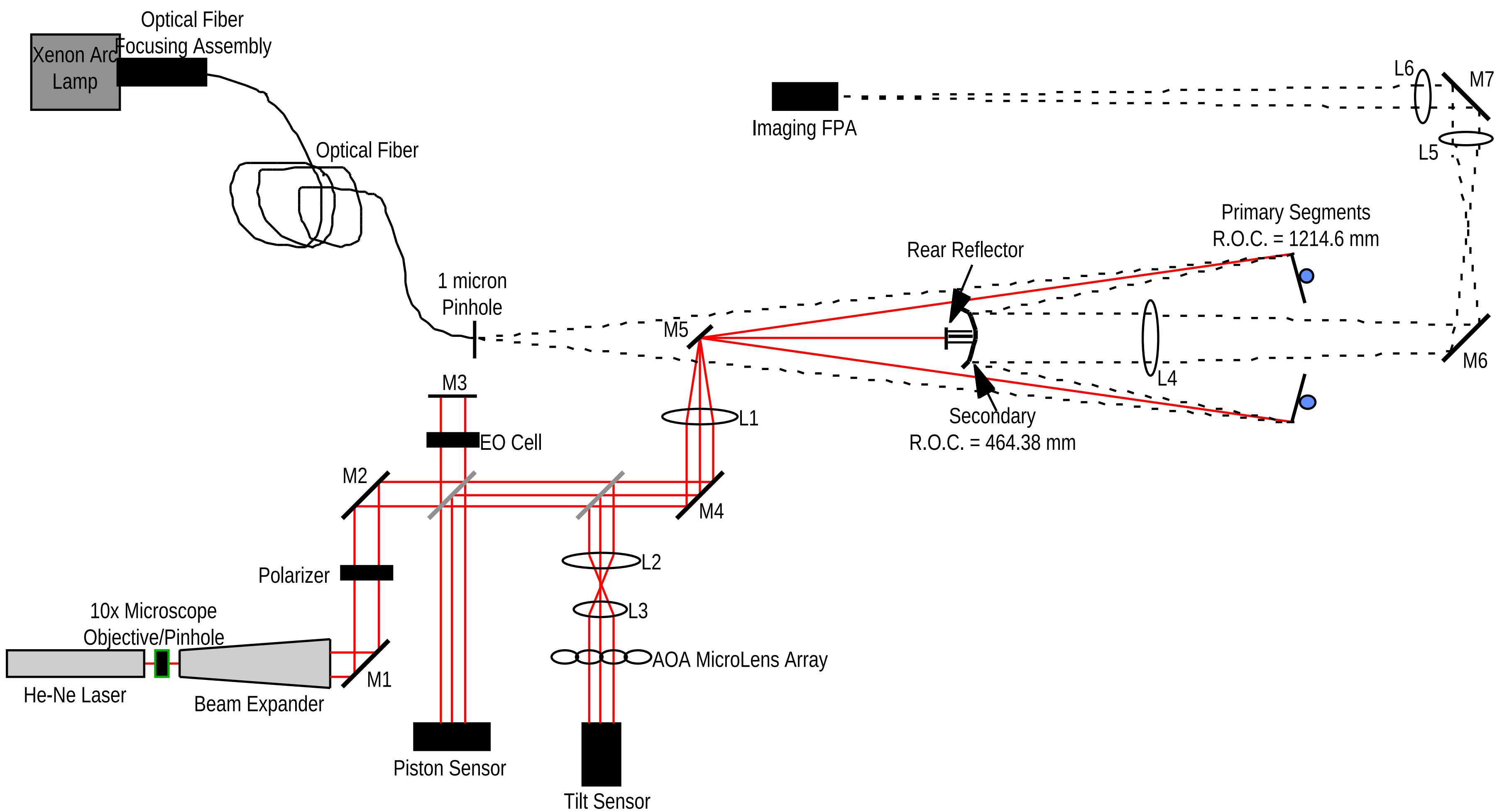
- Fringe Visibility* 0.22 — Fringe Spacing 2.18 ur
  - Optical Quality 0.43
    - Primaries 0.53
      - Radius Error 0.90 — 0.02% mismatch
      - Sphr Abberation 0.65 — 0.1 wave P-V**
      - Astigmatism 0.91 — 0.1 wave P-V
    - Secondary 0.81
      - Sphr Abberation 0.90 — 0.25 wave P-V
      - Astigmatism 0.90 — 0.25 wave P-V
  - Alignment 0.75
    - Primaries 0.91
      - Tilt 0.91 — 0.15 waves — 1.8984 ur
      - Piston 0.99 — 38 nm
    - Secondary 0.91
      - Tilt 0.91 — 0.22 ur (O.S.) — 0.95 ur (mirror tilt)
      - Focus 0.99 — 1 mm
    - Source 0.91
      - Translation X and Y 0.91 — 0.22 ur — 0.3498 um
      - Translation Z 0.99 — 1 mm
  - Disturbances 0.80
    - Atmospheric 0.93
    - Unrejected Mechanical 0.93
    - Thermal 0.93 — 0.4 waves OPD — 0.17 deg C
  - Detector Sampling 0.95 — 5 pixels/(lambda/D) — 0.436 urad/pix
  - SNR 0.90 — 20 SNRpk

* Visibility = Strehl x Fringe Contrast

** Waves P-V are relative to reflected wavefront (allowed surface errors are 1/2 as big)

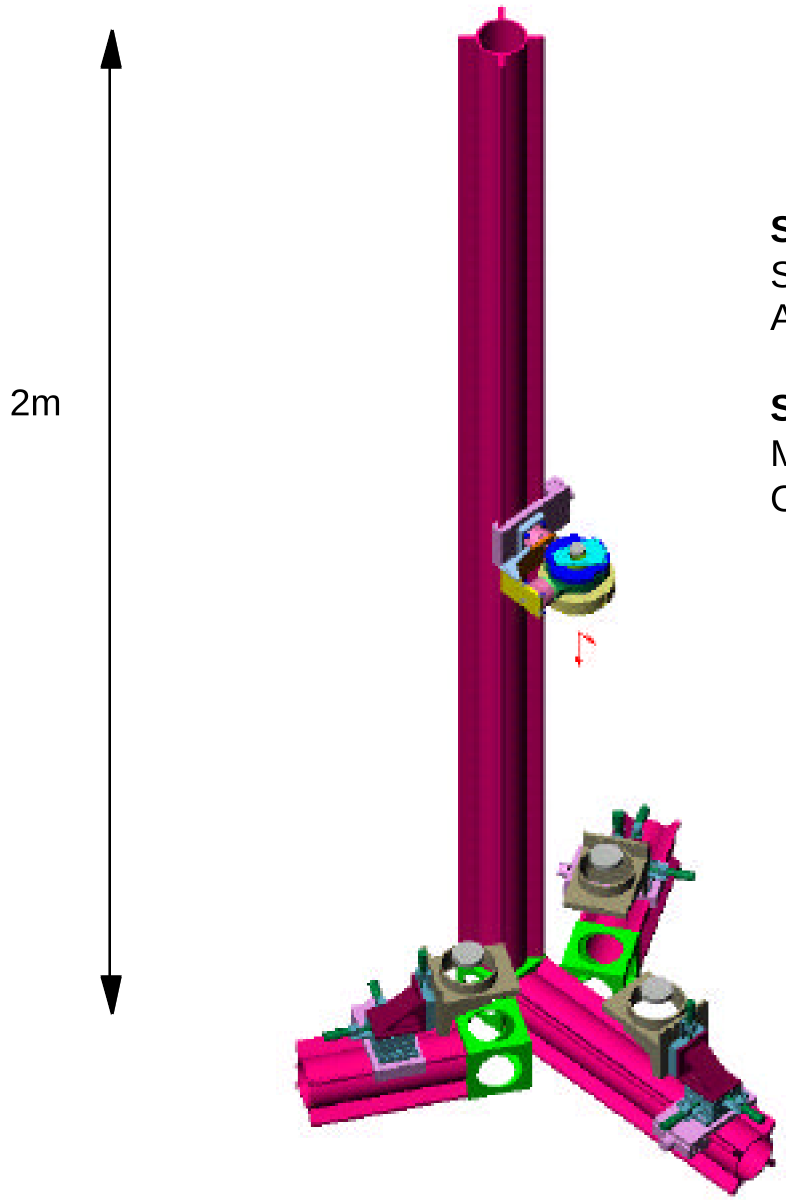
LCSI Experiment 2-D Optical Setup

Interim setup for automatic phasing demo



LCSI Lab Structure

Final setup for 3 aperture phasing demo



Structure allows space telescope emulation

Sizing is consistent with inner 3 primaries of Golay 6

Allows single point disturbance input to optical system

Status

Mechanical design near complete - custom interface plate

Off-the-shelf optical rails ordered and received

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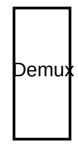
Tilt and Piston Control Diagram

Matlab/Simulink design environment creates real-time code

External
Outputs

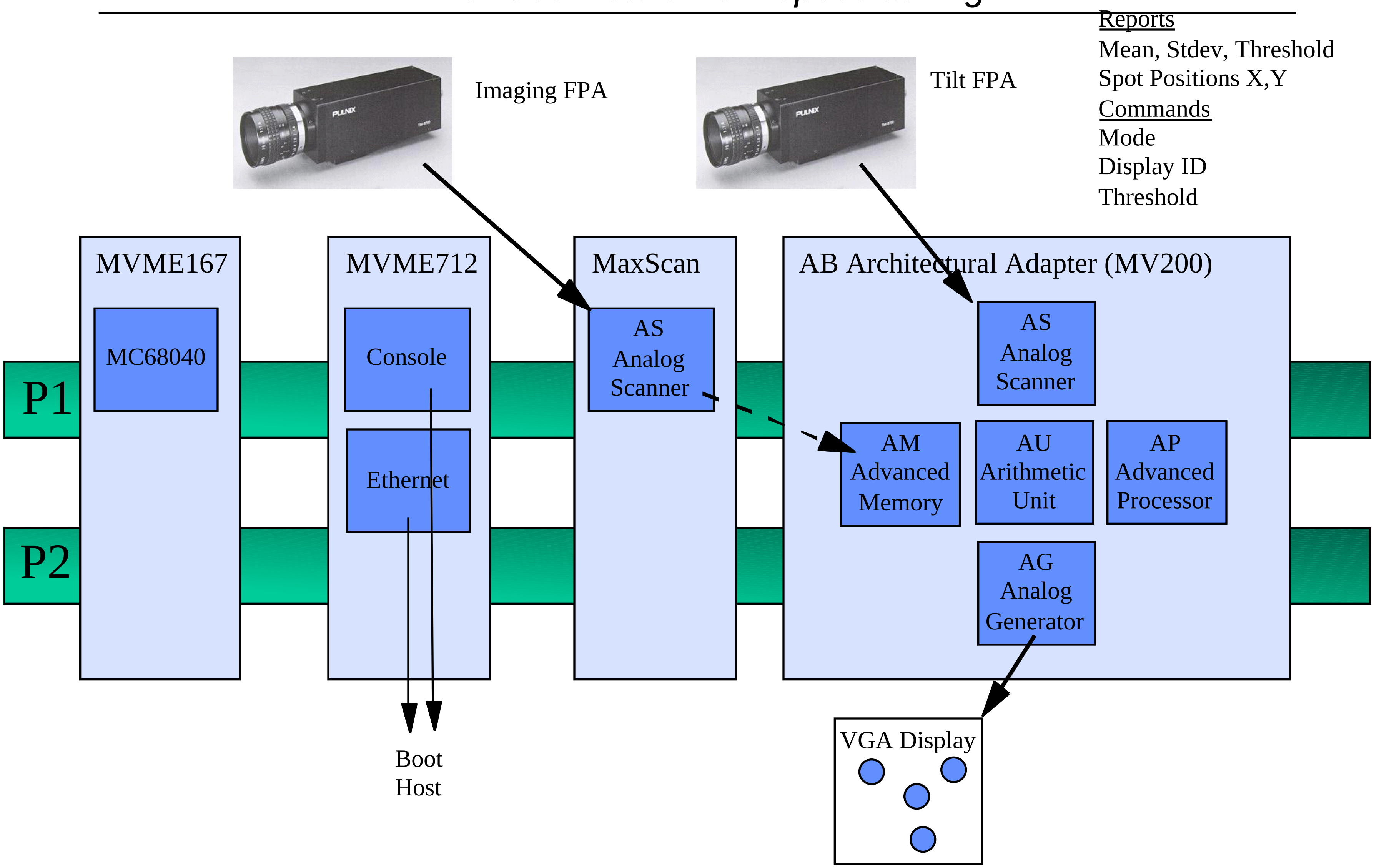


External
Inputs

Matlab/Simulink Design Environment
Diagram includes “buzz” test and mode logic

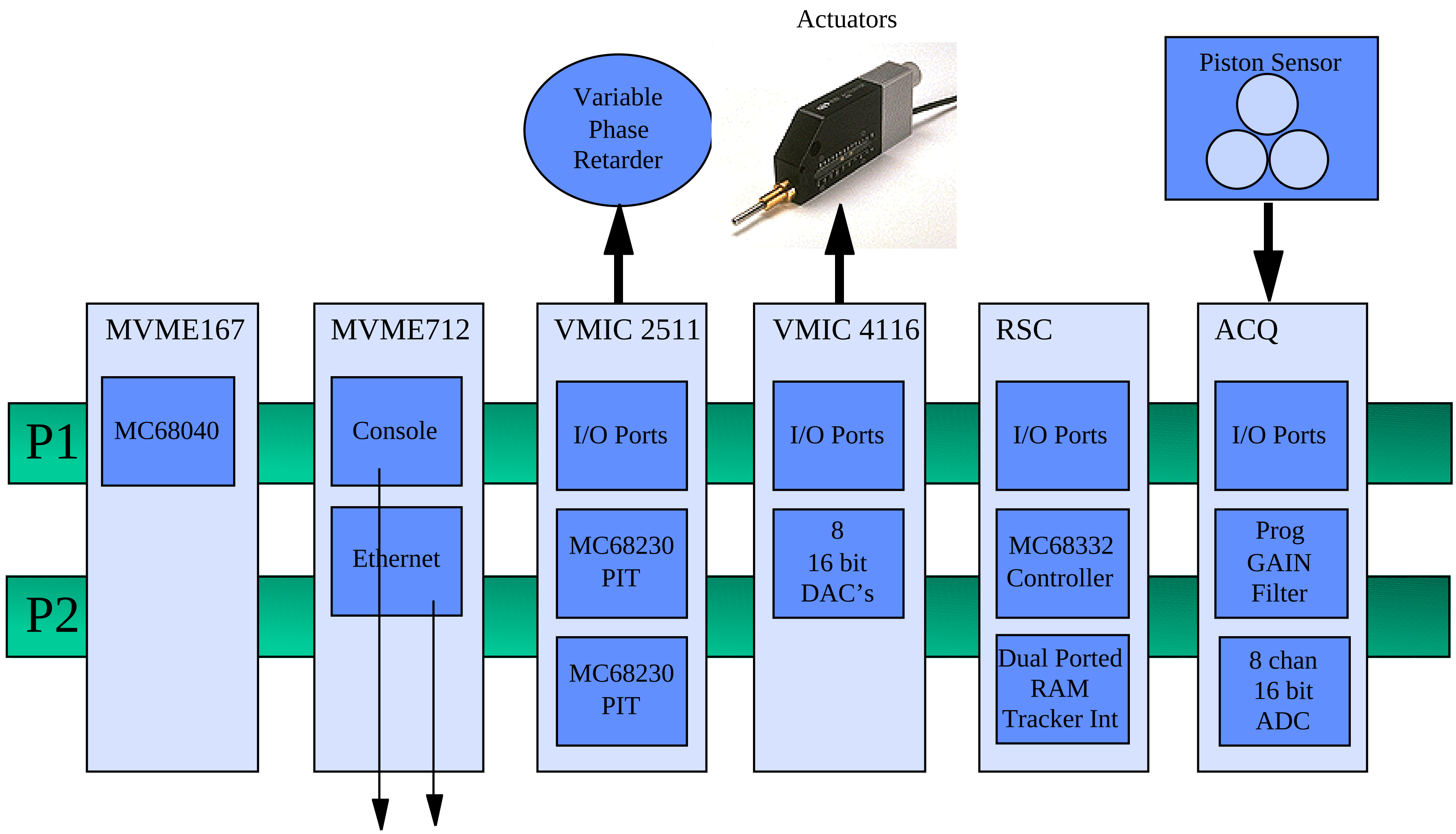
Track Computer Processing

Provides Real-time 4 spot tracking



Controls Computer Processing

Executes Matlab/Simulink Real-time Code



Autonomous Tilt and Piston Loop Closure

x buzz

y buzz

tilt loops
close

piston loop
close

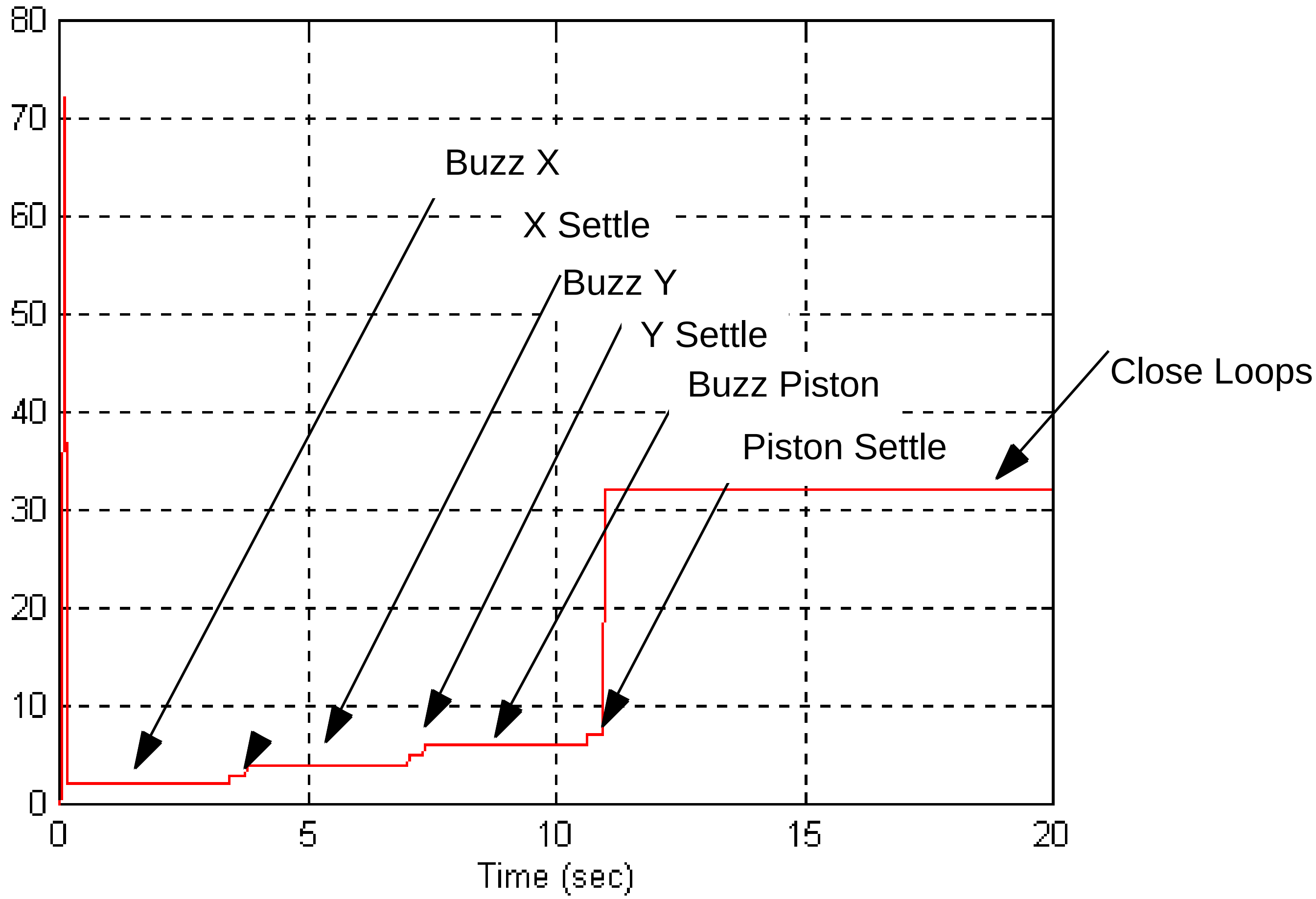
Residual Piston is consistent with Error Budget

50 nm (0.08 waves) OPD -> 25 nm Mirror motion (38 nm requirement)

Residual Tilts are scaled by 20X in next config. - consistent with 2 ur requirement

Automatic Mode Logic

Phasing involves a specific event sequence



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Summary and Conclusions

Developed optical controls architecture for a viable space concept

Experimental validation of this concept is underway

Technologies and capabilities being developed on LCSI are highly relevant to NGST space concept development and risk reduction experiments